THE PETROLOGY OF THE HARTLEY DISTRICT. II.

The Metamorphosed Gabbros and Associated Hybrid and Contaminated Rocks.

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(Plates v–vi; four Text-figures.)

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Introduction.

In the following pages an account is given of certain rocks of mixed origin that have been produced as a result of (1) interaction between a solid gabbro and a quartz-mica-diorite magma, (2) contamination of the gabbro by sediments. The thermal metamorphism of the gabbro, due to the emplacement of the more acid rock. is also considered.

The writer has previously (1931) described a calcic plutonic complex ranging from acid granites through an intermediate and basic series down to the ultrabasic type—hornblendite. Chemical analyses were made to show the consanguinity of the types, and although it was realized that the gabbros had suffered contact metamorphism, the present more detailed study of these phenomena has revealed the fact that the rock analysed for a pyroxene-gabbro (Joplin, 1931, p. 43) is a hybrid formed by the interaction between the solid gabbro and quartz-mica-diorite magma. Further studies, however, the examination of ninety-one microsections, and two more analyses have shown the two intrusions to be comagmatic and the rock previously analysed to be but slightly acidified. Furthermore, it can now be shown that the hornblendites are hybrids and of the nature of basic segregations.

The mass under examination has been referred to previously as the Cox's River Intrusion, and outcrops on Cox's River about 3 miles below the Glenroy Bridge on the Jenolan Road. A small portion of the mass outcrops within the Parish of Hartley, County of Cook, but the greater part of it lies to the west of the river in the Parish of Lowther, County of Westmoreland.

Field Relations.

The Cox's River Intrusion, and the Moyne Farm Intrusion, a composite diorite stock 1¼ miles to the east (Joplin, 1931), are injected into the trough of a syncline trending approximately east and west and pitching to the east. This is occupied by Upper Devonian sediments and lavas. Granite outcrops to the north and south of the syncline and its junctions are roughly concordant with the strike of the sediments. Both to the north and to the south the broad syncline is turned over abruptly into a sharp anticline against the margin of the granite. This possibly may be due to a drag effect of the invading granite.

The Cox's River Intrusion occupies an area of about 900 acres, but a fairly large outcrop of quartz-mica-diorite in Por. 52, Parish of Lowther, suggests that the acid phase is more extensive than at present appears to be the case. The centre of the main mass is situated in Por. 137, Parish of Lowther, and the rocks at the junction of the creeks at this point appear to be normal hornblende-

* This work was commenced when the writer held a Sydney University Science Research Scholarship in Geology and the Deas-Thomson Scholarship for Mineralogy.

gabbros that have suffered a slight deuteric alteration. Reference to Plate v shows that passing out radially in any direction a recrystallization becomes apparent. A partial granoblastic structure is developed, and monoclinic and rhombic pyroxenes are the only ferromagnesian minerals. Further out still hornblende again makes its appearance and a fabric resembling the primary ophitic gradually comes into evidence. Isolated outcrops of diorite-gabbro and hornblende-gabbro occur among the hornblende-pyroxene-gabbros, and scattered through these latter and also through the recrystallized pyroxene-gabbros are rocks that have suffered hydrothermal alteration, the pyroxene having been changed into pale uralitic material. A mass of quartz-mica-diorite, varying in width from 10 chains to half a mile, completely encompasses this gabbro complex, and it has been pointed out already that there is reason to believe that these rocks are even more widespread.

Form of the Quartz-mica-diorite Intrusion.—Although the quartz-mica-diorite encircles the gabbro, there is some evidence to show that the engulfment was not of a normal type. It seems evident that the junction between the diorite and the gabbro is convex upwards and that the thickness of diorite on top of the gabbro was not very appreciable.

Plate v shows that near the head of Marriott's Creek there is a mass of quartzite (15 × 10 chains) resting partly on the surface of the gabbro, and about 10 chains to the west of this a small patch of highly altered porphyrite occurs. As porphyrites are found interbedded with the sediments elsewhere in the district, it is probable that this, together with the quartzite, represents a portion of the roof of the intrusion. This would indicate that either the quartz-mica-diorites did not cover the gabbro, or that the mass is portion of a "roof-pendant" (Daly, 1906) protruding down below their level into the underlying gabbro. A large mass of sediments occurs near the margin of the granite about a mile further up the river, and a small patch among the diorites on Moyne Farm, and small outcrops of granite and diorite, at short distances from the main intrusions, are not infrequent. These occurrences suggest that the sedimentary cover of the bathylith has not yet been completely removed, and that no very deep denudation has taken place. This, together with the fact that the gabbros often occupy the higher levels of the Cox's River Intrusion, inhibits the possibility of a very deep protuberance of sediment, and points either to a very thin cover of diorite or to no such cover at all.

Reference to Plate v shows that, although the quartz-mica-diorite is of fairly constant width, that of the "reaction-ring" of hornblende-pyroxene-gabbro is rather irregular; and, moreover, that this irregularity appears to bear no relation to the present width of the diorite. These facts seem to point to a covering of diorite which was apparently of no very great thickness. An inwardly curving junction between the two igneous rocks is also indicated.

The form of the intrusion is possibly that of a hollow cylinder with a dome-like roof and a ring-like outcrop. The annular width is fairly constant and approximately 20 chains, whilst the diameter of the enclosed gabbro mass is of the order of 60 chains. There appears to be only one radial apophysis into the gabbro. This annular form may be accidental, though the intrusion appears to have some affinities to the ring-dykes so common in certain parts of Scotland (Bailey *et al.*, 1924; Richey and Thomas, 1930; Richey, 1931).

A wide valley occupies the centre of the intrusion and this is surrounded by steep hills. The physiography is certainly peculiar and is suggestive of down-faulting, especially in view of the ring-like structure of the intrusion. There is no evidence of faulting, however, and although the structure of the intrusion is significant, it is impossible to admit a large sunken area.

Petrography.

i. *Deuterically altered hornblende-gabbros.*

The hornblende-gabbros occupy a small area in the centre of the intrusion on the property of Mr. Chris Commens, Por. 137, Parish of Lowther, and show little or no evidence of having suffered contact metamorphism. They are heavy dark rocks with a variable grainsize, and in the handspecimen are seen to consist of plagioclase, hornblende and iron ore.

Under the microscope they are ophitic to subophitic, and the grainsize is usually medium (2 mm.–3 mm.). The constituent minerals are plagioclase, hornblende, augite, hypersthene, iron ores, apatite and sometimes a little biotite and quartz. Epidote, chlorite, kaolin, saussurite, iddingsite, (?) lawsonite and a zeolite are present as products of deuteric action.

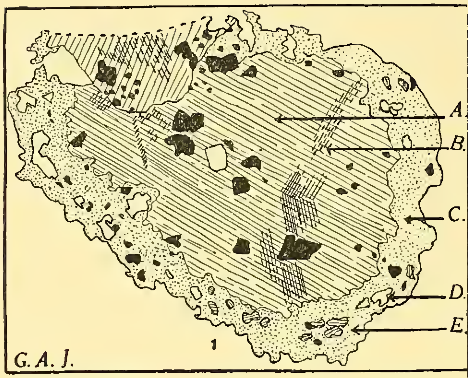
The plagioclase occurs in idiomorphic to subidiomorphic crystals with a stout columnar or somewhat tabular habit, and is partly wrapped round by, or included in the femic minerals. The composition is labradorite ($Ab_{37}An_{63}$), but occasionally a slight zoning is present. Twinning is well developed after the albite law, and sometimes pericline twinning is present. A few small indeterminate inclusions occur, and the felspar shows a good deal of alteration into epidote, saussurite and kaolin.

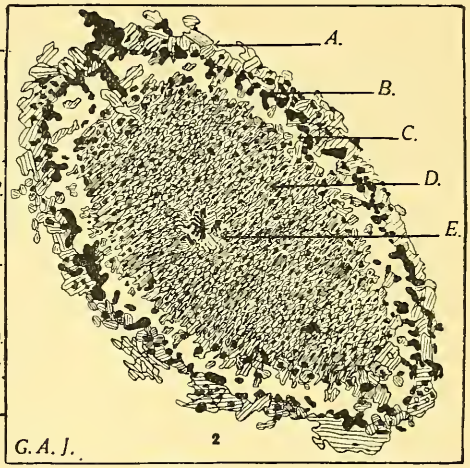
The hornblende forms large subidiomorphic columns or irregular sheets, and often encloses cores of pyroxene about which it is forming a reaction-rim (Bowen, 1922*a*). Simple pinacoidal twinning is fairly common, and small inclusions of iron ore abundant. The colour is brownish-green and the absorption $Y >$ or $= Z > X$.

Augite sometimes forms subidiomorphic columnar crystals, but is more often rounded and corroded and surrounded by a reaction-rim of hornblende (Plate vi, fig. 1). Magnetite grains are usually present as inclusions, and in those rocks that show slight evidence of recrystallization, the augite has developed schiller inclusions in restricted patches. In the opinion of Judd (1890) and H. H. Thomas (1930, p. 239) local schillerization is of a secondary origin and may evidence thermal metamorphism. Harker (1904, p. 109), however, considers that "the capricious distribution does not seem inconsistent with a primary origin". In a section showing slight evidence of thermal metamorphism (Text-fig. 1) one set of schiller inclusions subtends an angle of 84° with the prismatic cleavage of the pyroxene, and the second set subtends an angle of 137° with the first. In the same microsection small granules of recrystallized pyroxene occur in the brown hornblende which is forming a wide reaction-rim about a large columnar section of original augite (Text-fig. 1). Besides the "reaction" change to primary hornblende, the augite often shows evidence of having suffered deuteric alteration, and has been partly converted into uralite.

Iron ores, apparently consisting of both magnetite and ilmenite, occur in two generations. The first generation is represented by small inclusions in all the other minerals; the second by fairly large irregular grains moulding both felspars and ferromagnesian minerals. Small flakes of biotite are intimately associated with the iron ores in a few specimens, and in these tiny interstitial grains of quartz are also present. As the rocks containing biotite and quartz also show slight evidence of thermal metamorphism, it was at first believed that the biotite was produced as a result of recrystallization as observed by Dr. Tilley

(1924) in the contact altered epidiorites at Comrie. As no biotite occurs in the more completely altered types, to be described below, it is concluded that these rocks represent slightly more acid differentiates of the hornblende-gabbro.





Text-fig. 1. Text-fig. 2.

Text-fig. 1.—A, pyroxene; B, local schillerization; C, reaction-rim of brown hornblende; D, plagioclase; E, recrystallized pyroxene.

Text-fig. 2.—A, pyroxene-rich zone; B, iron ore-rich zone; C, plagioclase-rich zone; D, fine granular aggregate; E, coarse granular aggregate.

(?)Lawsonite (Ransome, 1904; Stillwell, 1923; Joplin, 1931) sometimes forms lenses in the biotite.

Hypersthene is developed in rounded columnar crystals in a few specimens, and may represent a product of metamorphism, since it occurs in those rocks exhibiting incipient recrystallization. Occasionally iddingsite is associated with the hypersthene.

A zeolite is developed in a few of the hornblende-gabbros. It consists of masses of either unoriented or radially arranged fibres which occupy interstitial spaces or veins in the rock. Small veins of a secondary amphibole sometimes occur, and in these the amphibole fibres are arranged at right angles to the walls of the vein.

ii. *Recrystallized pyroxene-gabbros.*

The pyroxene-gabbros surround the hornblende-gabbros and, indeed, some of them cannot be distinguished from the hornblende varieties in the hand-specimen. They vary from fine-grained types to fairly coarse rocks which can be seen to consist of plagioclase, pyroxene and iron ores.

Under the microscope the pyroxene-gabbros usually show a blastosubophitic structure, but a granoblastic structure is often locally developed (Plate vi, fig. 2). The grainsize is mainly even and medium, and the rocks may be divided roughly into two types—those in which there is but slight or no apparent recrystallization of the felspar, and those in which the felspar is partly granular. The field-relations of these are quite irregular. The constituent minerals are plagioclase, hypersthene, augite, iron ores, uralite, a little apatite, a trace of brown hornblende and sometimes iddingsite and a talcose mineral.

In those rocks in which only slight recrystallization of the felspar has taken place, the plagioclase forms columnar crystals about 1 mm. in length. If any granular felspar be present in this type, it forms small equidimensional grains of about 0·05 mm. In the rocks containing partly recrystallized felspar it forms either stout columnar or tabular crystals that are indented by the small granular felspars and pyroxenes surrounding them. In these types the proportion of granular to columnar felspar is greater, and in a few cases the larger plagioclase crystals have become so indented by the surrounding granules that the rock appears to be quite granular. In a few slides there is a slight indication of bending in the longer columnar plagioclase crystals. The plagioclase is labradorite, but the composition varies in the different specimens from $Ab_{48}An_{52}$ to $Ab_{32}An_{68}$, and zoning is usually absent. In a few specimens, however, inverted zoning is present. This structure has been noted by Dr. W. R. Browne (1927) in metamorphosed dolerites from Broken Hill. The most remarkable feature of the plagioclase is a peculiar clearing and the presence of groups of minute inclusions. These inclusions are crowded in the centre of the felspar or arranged in zones (Plate vi, figs. 2, 6). They usually appear as small, dark brown dots, and in a few cases tiny granules of pyroxene have been recognized. This clearing and the formation of minute inclusions has been noted by A. Harker (1904), C. E. Tilley (1921) and W. R. Browne (1927). Dr. Browne has shown that many of the granules in the Broken Hill rocks consist of pyroxenes and brown hornblende, and Dr. Tilley has suggested a similar identification. The completely recrystallized felspars are quite limpid and free from inclusions. In a few instances the centre of a plagioclase crystal is occupied by a pale brown, anisotropic mineral, which suggests an incipient alteration into brown hornblende.

In some of the specimens augite is present both as idioblastic, columnar crystals, which usually show sieve-structure, and as small rounded columnar crystals or granules crowded between the felspars and indicating the original ophitic fabric of the rock. The fabric of the rock is thus an intergranular one produced by metamorphism and may perhaps be termed intergranoblastic. In many specimens the rounded columnar and granular pyroxene is the only type present. In some cases the larger crystals have become granulated, though the original shape of the crystal is preserved. Schiller inclusions are fairly common, and the crystals exhibiting sieve-structure are crowded with small rounded inclusions of plagioclase, iron ores and (?)quartz. An intergrowth between the pyroxenes is quite frequent, and twinning is often developed. Many of the larger augite crystals are flecked with brown hornblende, suggesting a state of incomplete equilibrium. In one slide a talcose material has been noticed filling cracks in the pyroxene. This is possibly due to a later period of hydrothermal metamorphism, which is also evidenced by the development of a secondary amphibole in the pyroxenes along cracks in some of the rocks.

Hypersthene shows exactly the same features as the augite, from which it may be distinguished by its lower double refraction, straight extinction and pleochroism. The pleochroism is comparatively strong for this mineral, which suggests a fairly high percentage of iron. This high iron content is further indicated by the frequent development of limonite along cracks in the hypersthene. In a few specimens iddingsite is associated with the rhombic pyroxene.

Iron ores are extremely fresh, but occasionally a little granular sphene is associated and it is probable that both magnetite and ilmenite are present. The iron ores occur as small inclusions in the other minerals, or as very irregular grains, up to 1 mm. across, moulding the felspars. These latter are in close association with the granular pyroxenes, which are crowded between the felspars, and may represent a recrystallized original iron ore and/or a recrystallization product of the original ferromagnesian mineral that moulded the felspars.

In most of these rocks apatite is present only in small amount and may sometimes be absent. When present it forms fairly large, stout columnar crystals, and is moulded by the magnetite and pyroxenes and occasionally by the plagioclase.

In a few of the pyroxene-gabbros, as well as in some of the recrystallized types that have suffered reaction and/or hydrothermal metamorphism, ellipsoidal masses of granular augite, hypersthene, plagioclase and iron ores occur. These may be up to 10 mm. in length and have a peculiar zoned arrangement of the constituent minerals (Text-fig. 2). Though not always perfectly zoned, the following arrangement may usually be made out. In the centre there is a core of poikilitic plagioclase and moderately large pyroxene and magnetite granules, or a fairly coarse granular mass of these three minerals. This is followed by a wide rim consisting of an extremely fine granular mass of the same three minerals and then by a magnetite-pyroxene-rich zone which is narrower and a good deal coarser in grain. Outside this again comes a felspar-rich layer, then a zone very rich in iron ores, and finally one consisting exclusively of pyroxenes. The wide fine-grained zone, and the coarser-grained central zone show some variations. In one of the ellipsoids a cruciform arrangement has been noticed. The coarser area forms a cross which divides the finer outer zone into four sectors. In another the coarse zone is very wide in comparison to the finer, and in others again it is quite eccentrically placed. Some sections of these bodies show a remarkable parallelism of the longer axes of the granules. In the hand-specimens the ellipsoids are not readily distinguishable and appear as small, dark, stony masses.

In column I below an analysis is given of a fairly normal type of the rock, and in column II the results of an analysis of a slightly leucocratic type is shown.

	I.	II.	III.
SiO_2	44·52	44·79	44·40
Al_2O_3	21·32	19·56	20·55
Fe_2O_3	5·08	6·01	6·57
FeO	7·19	7·79	9·26
MgO	6·41	6·16	5·21
CaO	12·44	11·81	11·50
Na_2O	1·25	1·21	1·14
K_2O	0·15	0·06	0·19
H_2O+	0·37	0·64	1·00
H_2O-	0·06	0·10	—
TiO_2	1·04	1·14	—
P_2O_5	abs	0·18	—
MnO	0·09	0·15	—
CO_2	tr	tr	—
Total	99·92	99·60	99·82
Specific Gravity	3·050	3·055	3·035

Quartz	—	2·04	0·96
Orthoclase ..	0·83	0·56	1·11
Albite	10·48	9·96	9·43
Anorthite ..	52·26	47·82	50·32
Diopside ..	7·42	8·10	5·50
Hypersthene ..	18·28	19·14	21·90
Olivine ..	1·21	—	—
Magnetite ..	7·42	8·82	9·51
Ilmenite ..	1·98	2·13	—
Apatite	—	0·34	—

I.—Recrystallized Pyroxene-gabbro (leucocratic phase). South end of Por. 239, Par. Lowther, Little Hartley (Corsase, near Kedebekase and Hessose, II(III), 5, (4)5, 3″). Anal. G. A. Joplin.

II.—Recrystallized Pyroxene-gabbro (normal type). North end of Por. 32, Parish of Lowther, Little Hartley (Kedebekase, near Corsase and Hessose, (II)III, 5, (4)5, 5). Anal. G. A. Joplin.

III.—Segregation in Norite. The Bluff, Otago, N.Z. (Corsase, II(III), 5, ″5, 0). Anal. L. J. Wild. *Trans. N.Z. Inst.*, xliv, 1911 (1912), p. 325. In W.T., p. 552, No. 10.

These analyses, particularly the one given in column II, show that the chief characteristics of the rocks are their high alumina and iron percentages and low potash. The chemical composition of the gabbro would suggest that it had affinities with the eucrites, and this is confirmed to some extent by the presence of very basic labradorite. According to Holmes (1920) a true eucrite contains bytownite-anorthite and pyroxene.

iii. *"Reaction"-gabbros or hornblende-pyroxene-gabbros.*

Reference to Plate v shows that the hornblende-pyroxene-gabbros form an outer border or reaction-ring about the recrystallized pyroxene-gabbros, and the following petrographical descriptions will serve to show that this group has suffered recrystallization, as well as reaction with the quartz-mica-diorite magma.

The hornblende-pyroxene-gabbros vary a great deal in the handspecimen. They are mostly dark, heavy, fairly coarsely crystalline rocks, often showing large "shimmer" plates of hornblende, crowded with inclusions, and giving both a porphyritic and poikilitic texture to the rock. Under the microscope the structure is partly granoblastic and often blastoporphyritic and poikilitic. Besides this the reaction hornblende has given rise to a fabric similar to the primary ophitic (Plate vi, figs. 4, 5). The grainsize varies in the different specimens from 3 mm. to less than 1 mm. The minerals composing these rocks are plagioclase, augite, hypersthene, brown hornblende, magnetite, ilmenite, chlorite, epidote, uralite, apatite, (?) rutile, and a zeolite.

In the blastoporphyritic types the plagioclase phenocrysts are tabular, whilst that of the groundmass forms small laths or is partly granular. Many of the felspars show an inverted zoning, with a later outer rim of more acid plagioclase. The acid core and selvage are of basic andesine and the middle zone consists of basic labradorite ($Ab_{32}An_{68}$). The addition of more acid felspar from the invading magma is also indicated by a peculiar mottled appearance of some of the larger tabular crystals. As in the pyroxene-gabbros, the plagioclase shows a characteristic clearing and the development of minute inclusions, and occasionally schiller inclusions may be seen within the tiny inclusions of pyroxene in the felspar. Besides this clear felspar there is a little cloudy plagioclase sometimes developed. Under the low power objective this appears as a greyish cloudiness which may be resolved under the high power into minute dark brown dots similar to, though much smaller than, the tiny inclusions of iron ore in the cleared felspars. Clouding and granules are often present together in the same felspar crystal and the clouding may be confined to definite zones or lamellae of the plagioclase. The most noteworthy feature of the felspar of these rocks is its apparent reaction with the invading magma to form brown hornblende (Plate vi, fig. 4). This process was noticed as an incipient change in some of the specimens of the last group, but among the hornblende-pyroxene-gabbros the process is far advanced and large sheets of basaltic hornblende appear to be threaded in between the plagioclase crystals and often enclose them. Where hornblende has become an important constituent of the rock, it may be seen encroaching along cleavage planes and forming embayments in the felspar.

Augite and hypersthene are developed in subidioblastic columns or small xenoblasts. In a few cases the larger columnar pyroxenes are grouped, indicating a glomeroporphyritic fabric in the original rock. In one slide these groups show a rosette-like arrangement as observed by Dr. C. E. Tilley (1921) in some of the metadolerites from Eyre's Peninsula, South Australia. Schiller inclusions or a heavy discharge of secondary magnetite, often in a dendritic pattern, sometimes mask the nature of the original pyroxene. Both augite and hypersthene are flecked with brown hornblende and are usually surrounded by a wide reaction-rim of the same amphibole. The rounded and corroded appearance of the pyroxene crystals testifies to the origin of the brown hornblende. In a few slides masses of iddingsite are pseudomorphing the hypersthene. This change is probably deuteric and has been recorded as such in the hypersthene-andesites of Blair Duguid by W. R. Browne and H. P. White (1926). The basaltic hornblende shows undoubted evidence of a secondary origin, and apparently arises as a result of reaction between the invading magma and both plagioclase and pyroxenes. It forms large irregular crystals up to 5 mm. across, and is highly poikilitic, enclosing partly dissolved and corroded crystals of the minerals from which it has originated. The absorption is $Z >$ or $= Y > X$. In a few rocks situated close to the quartz-mica-diorites, the hornblende is a less basic type and is greenish-brown in colour. In some of the sections an outer border of bluish-green soda-bearing hornblende has been noted.

The small ellipsoidal bodies, showing a zoned arrangement, and consisting of granular plagioclase, pyroxene and iron ores, are fairly common amongst this group of rocks. Occasionally they are surrounded by a reaction-rim of brown hornblende.

One rather unique specimen of hornblende-pyroxene-gabbro has been collected in which much of the brown hornblende is idiomorphic. Tiny acicular felspars are crowded between slightly more basic plagioclase laths and these little needles are abundant as inclusions in the ferromagnesian minerals.

iv. *Hornblendites.*

The hornblendites occur in small rounded, lens-like or vein-like masses in the "reaction"-gabbros, and are particularly abundant in the northern part of Por. 237, Parish of Lowther, on the property of Mr. Chris Commens, and in the southern part of Por. 27, immediately north of Por. 237, on the property of Mr. D. Mitchell.

These rocks have already been described in some detail (Joplin, 1931), and little further need be said regarding their petrography. It might be pointed out, however, that although these small ultrabasic masses were previously regarded as xenoliths, it was suggested, on account of their vein-like appearance, that they might represent basic segregations. It was further suggested that the rocks are hybrids on account of the comparatively low specific gravity, relatively acid felspar (andesine) and the presence of small quantities of quartz. The fact that a fairly acid mesostasis is present also points to hybridization. The occurrence of zoned hornblende with a sodic border suggests reaction, and calcite, epidote and uralite indicate deuteric activity.

v. *Diorite-gabbros and hornblende-gabbros.*

A group of rocks termed "diorite-gabbros" was described by the writer (1931), and it was considered that these formed a reaction-ring about the pyroxene-gabbros.

The present study on metamorphism, however, has revealed the fact that these rocks are not so abundant as at first appeared, and many of the rocks thought to have been diorite-gabbros now prove to have suffered an earlier recrystallization and can be assigned to the group of hydrothermally altered gabbros described below.

The rocks that are now considered to be diorite-gabbros occur in isolated patches among the quartz-mica-diorites and "reaction"-gabbros, and as their appearance is often very similar to the contiguous rocks, it is likely that they are far more abundant than at present appears to be the case.

The name diorite-gabbro has been retained for this group as the rocks have an ophitic or subophitic fabric and the chief ferromagnesian mineral is green hornblende such as is common in the diorites. They are, however, decidedly more basic than the quartz-mica-diorites, and the felspar is a labradorite, which characterizes the gabbros. It will be shown later that these rocks are possibly hybrids due to the contamination of the quartz-mica-diorite magma by solid gabbro, so the name "diorite-gabbro" seems quite fitting and satisfactory.

In the handspecimen the diorite-gabbros have the appearance of diorites and seem to consist of hornblende and plagioclase in about equal proportions. On Marriott's Creek and near the head of Hughes' Creek these rocks have a rude banding and are slightly richer in felspar.

Under the microscope the diorite-gabbros are seen to have an ophitic and poikilitic fabric and to consist of plagioclase, brownish-green or green hornblende, iron ores, occasionally augite, and in a few specimens a little quartz and biotite. Secondary sphene, epidote, chlorite and kaolin bear testimony to a period of deuteric activity or hydrothermal metamorphism.

The plagioclase is exceptionally abundant, especially in the banded types. It is labradorite ($Ab_{50}An_{50}$),* and is occasionally zoned. The centres of the felspar sometimes show alteration into sericite and kaolin, whilst the outer borders are quite clear. In one slide the banded nature of the rock is accentuated by the parallel arrangement of the plagioclase laths.

The hornblende is either green or greenish-brown and forms highly poikilitic patches about 1·5 mm. across. In the banded types these patches are arranged in linear fashion. The more idiomorphic hornblende crystals are sometimes surrounded by a bluish-green sodic border.

In one specimen fresh augite is present as well as hornblende and its poikilitic and linear arrangement is similar to that of the amphibole.

A little highly poikilitic biotite is present in a few slides, and is usually associated with (?)lawsonite and chlorite. Quartz is occasionally present as tiny interstitial grains, apatite is fairly abundant and iron ores, though not abundant, behave in a similar manner to the ferromagnesian minerals. The ilmenite is sometimes surrounded by grains of secondary sphene.

The hornblende-gabbros also have a sporadic distribution and in the handspecimen are dark, heavy, fairly coarse grained rocks consisting of plagioclase and hornblende.

Under the microscope they have an ophitic fabric and are seen to be composed of brown or dark brownish-green hornblende, pyroxene (usually completely uralitized), plagioclase, iron ores and apatite. A little quartz and biotite has been noted in a few specimens, and hydrothermal activity is evidenced by the presence of uralitized pyroxene, uralite veins, secondary magnetite, epidote and (?)lawsonite. In one slide an original hornblende crystal is pseudomorphed by tiny flakes of biotite and chlorite, which suggests a weak thermal metamorphism. Slight pneumatolysis is evidenced by the presence of a little pyrites

* It was previously stated (1931) that the felspar was occasionally as basic as $Ab_{43}An_{57}$, but these specimens have proved to be hydrothermally altered gabbros.

and tourmaline in a specimen near the boundary fence between portions 27 and 239, Parish of Lowther.

These rocks need not be described in detail, as they are very similar to the deuterically altered hornblende-gabbros in the centre of the intrusion, and their close similarity will be commented upon later.

vi. *Hydrothermally metamorphosed gabbros.*

Both the recrystallized pyroxene-gabbros and the "reaction"- or hornblende-pyroxene-gabbros have suffered hydrothermal alteration in sporadically distributed localities.

(*a*) *Altered pyroxene-gabbros.*

Like the recrystallized pyroxene-gabbros, the hydrothermally metamorphosed types show a great variety of textures, but an earlier partial granoblastic structure may usually be made out, thus showing that these rocks are altered recrystallized gabbros.

The mineral constituents are wholly or partly uralitized pyroxene, plagioclase, magnetite, ilmenite, apatite, chlorite, talcose material, secondary sphene and sometimes iddingsite, limonite and carbonates.

The original phenocrysts or larger pyroxene crystals are usually heavily schillerized or crowded with secondary magnetite grains arranged in a dendritic pattern; but those crystals that have suffered an earlier recrystallization do not show this discharge of iron ores to the same extent. Frequently the pyroxene is converted into a pale uralitic amphibole, and uralite veins are not uncommon (Plate vi, fig. 3). In cases of less extreme alteration the uralite may fringe the pyroxene. The hypersthene often shows cracks filled with a talcose material, or may sometimes alter into iddingsite. In a highly altered rock the pyroxenes show a good deal of carbonation.

The plagioclase evidences an earlier partial recrystallization, sometimes by its granular appearance, but more often by the presence of the characteristic small inclusions. A further change is noticeable in most of these rocks, namely, a cloudiness similar to that which has been observed in the "reaction"-gabbros. Clouding is often present in the same crystal as the minute inclusions and seems to be superimposed upon the original clearing. It is usually confined to definite zones of the felspar—most frequently to the sodic zones. It may also be confined to certain twin lamellae. Under the high power objective the clouding is resolved into tiny brown dots, smaller than those associated with the ferromagnesian granules of the partially recrystallized felspars. The dots suggest iron ores—possibly ilmenite. The plagioclase may also show streaks of chlorite and in a type that has suffered extreme alteration it is sericitized and kaolinized.

Ilmenite is usually surrounded by granules of secondary sphene, and apatite is a little more abundant in these rocks.

(*b*) *Altered hornblende-pyroxene-gabbros.*

There is little need for a detailed description of the altered hornblende-pyroxene-gabbros since they are essentially similar to the "reaction"-gabbros, and the hydrothermal changes are similar to those that have just been described for the altered pyroxene-gabbros. One further change, however, is worthy of note.

As in the "reaction"-gabbros, the brown hornblende often borders the pyroxenes, and in several of the hydrothermally altered types this reaction-rim is entirely altered into a mass of pale green actinolite fibres (strahlstein). The enclosed cores of pyroxene are heavily schillerized, and the talcose form of alteration seems more common among the hypersthenes in this group of rocks. Augite shows alteration into uralite, chlorite and carbonates.

vii. *Quartz-mica-diorites.*

A fairly detailed description and an analysis of these rocks have already been published, so little further need be said regarding them.

It has been pointed out that the quartz-mica-diorites form a ring-like outcrop about the gabbros and, though a little quartz and biotite are present, they are fairly typical diorites in the handspecimen.

Under the microscope the rocks are somewhat porphyritic in plagioclase, which is usually zoned. In a single crystal these zones have been observed to range from $Ab_{47}An_{53}$ to $Ab_{88}An_{12}$. Several specimens show small inclusions within the felspar and at first sight they appear similar to those described as characteristic of the partly recrystallized felspars. Examination under high power, however, reveals the fact that these inclusions are mainly biotite and magnetite, the former often arranged with their longer axes parallel to the elongation of their host (Joplin, 1931), and it would thus seem that their origin was different from that of the granules of the recrystallized felspar. Nevertheless, the possibility of a similar origin cannot be entirely disregarded and it is possible that some of the "phenocrysts" are xenocrysts caught up by the quartz-mica-diorite magma after the shattering and stripping of the outer margin of the gabbro. The large blocks of pyroxene-gabbro, etc., within the diorite mass testify that such a tearing away of the selvage of the gabbro did take place.

The deuteric alteration of the quartz-mica-diorites needs a little further emphasis, and it should be pointed out that the late-magmatic solutions were fairly rich in potash. The chief deuteric minerals are sericite, saussurite, kaolin, muscovite, carbonates, α-zoisite, epidote, chlorite, (?)lawsonite, and secondary sphene.

In one specimen from Marriott's Creek a large crystal of plagioclase about 4 mm. in diameter has a clear outer rim showing two cleavages, and the interior is occupied by a mass of saussurite associated with muscovite. Blades of muscovite are arranged approximately at right angles to one another and parallel to the cleavages in the outer rim of felspar. These appear to be threaded through the granular saussurite which consists of abundant α-zoisite, carbonates and a little albite. An inclusion of hornblende shows epidotization and a change into fibres of pale secondary hornblende. There is no reason for assuming this white mica to be the sodic variety—paragonite—and it has been demonstrated elsewhere (Browne and White, 1926, 1928) that potash solutions are active deuteric agents.

viii. *Hedenbergite-bearing gabbros.*

Only two specimens of hedenbergite-bearing gabbro have been collected, one on Hughes' Creek and the other on Marriott's Creek. Their relations to the surrounding rocks have not been satisfactorily ascertained, but in both cases they are close to the contacts. On Hughes' Creek the rock is adjacent to the southern margin of the intrusion, and on Marriott's Creek the presence of a mass of quartzite at approximately the same level and 16 chains to the north-west indicates the proximity of the roof.

In the handspecimen the two rocks are quite dissimilar. The Hughes' Creek type is a very coarse sage-green rock consisting of plagioclase and hedenbergite.

The Marriott's Creek variety is a fine grained, dark olive-green hornfels with a specific gravity of 3·008. Little can be made of its composition in the hand-specimen, but small aplitic veins and groups of tiny dark green resinous acicular crystals may be discerned.

Under the microscope the Marriott's Creek type can be seen to consist of three regions and shows recrystallization: (1) A region very rich in pyroxene and its alteration products; (2) a pyroxene-granulite with a little quartz; and (3) comparatively coarse quartz-felspar veins.

(1).—These areas consist of abundant crystals of green non-pleochroic pyroxene which is poikilitic towards tiny grains of quartz and clear untwinned plagioclase. These crystals usually measure about 0·5 mm. and are flecked with, surrounded by, or entirely replaced by, chloritic material, and along veins by a secondary amphibole. Tiny dark, indeterminate inclusions are numerous, and in these areas small subidiomorphic crystals of sphene are abundant.

(2).—These areas are similar to those described above, but the pyroxene crystals measure only about 0·07 mm. The plagioclase is zoned and very basic, the outer rim of the crystals being a little less so. The inner core is sometimes sericitized.

(3).—The felspar forms idiomorphic laths 0·75 mm. in length and is andesine. Carlsbad twinning is common and albite and pericline twinning sometimes present. A little orthoclase is associated and allotriomorphic quartz grains are fairly abundant. A few pyroxene crystals appear to be torn off from the adjacent granulite.

The Hughes' Creek type also consists of three regions: (1) a coarse area consisting essentially of hedenbergite and basic plagioclase; (2) a region composed of small grains of the same minerals; and (3) vein-like areas of small, acicular, more acid felspars associated with granular knots of pyroxene and fairly large grains of quartz. Quartz veins are also present. As in the hornfels type (Marriott's Creek) sphene is abundant and iron ores typically absent.

(1).—The pyroxene is pale greyish-green and forms large subidiomorphic columns up to 6 mm. in length. Both simple and multiple twinning are present, and the extinction measures 41½°. Diallage cleavage and occasionally a sahlite striation are present and the centres of many of the crystals are clouded with a minute dust, possibly the cut ends of schiller inclusions arranged along the sahlite direction. Slight flecking by brown hornblende and chlorite is common in the centre of the crystals and one is entirely pseudomorphed by a dendritic arrangement of iron ores (apparently ilmenite), in a mass of chlorite and tiny granules of sphene, felspar and quartz. The plagioclase forms large subidiomorphic to allotriomorphic grains. A few grains show slight evidence of clearing upon which is superimposed an alteration into kaolin, sericite and carbonates. Sphene forms interstitial grains up to 0·6 mm.

(2).—This region has a grainsize of about 0·1 mm. and the fabric is granular. Plagioclase, green pyroxene and sphene are the chief minerals. These areas appear to have suffered recrystallization.

(3).—These are vein-like areas and are made up of more acid acicular or lath-shaped plagioclase crystals, which sometimes show zoning, in association with the above mentioned minerals.

TABLE I.

Rock Group.	Evidence of Reaction.	Evidence of Deuteric Action.	Evidence of Recrystallization.	Evidence of Reaction or Partial Hybridization.	Evidence of Hydrothermal Metamorphism.
Deuterically altered hornblende-gabbros.	Cores of pyroxene with reaction-rims of hornblende. Biotite fringing iron ores.	Saussurite, epidote, etc.			
Recrystallized pyroxene-gabbros.			Partly granular pyroxene. Schiller inclusions in pyroxene. Development of abundant hypersthene. (Tilley, 1923, p. 417.) Some granular felspar. Clearing of felspar with production of minute granular inclusions. Inverted zoning in felspar.		
Hornblende-pyroxene-gabbros or "Reaction"-gabbros.			Do.	Development of hornblende around partly recrystallized pyroxene and felspar. Mottling and zoning and clouding of felspar.	
Hydrothermally metamorphosed "Reaction"-gabbros.			Do.	Do.	Uralite, Strahlstein, etc. Clouding of felspar.

Petrogenesis.

i. *Possible Origin of the Various Rock Types.*

Many petrologists, who have studied contact metamorphism, J. Barrell (1907), V. M. Goldschmidt (1911), E. P. Dolan (1923), H. H. Thomas and E. B. Bailey (1924), and others, have shown that two stages of metamorphism may often be recognized: first, a thermal stage or recrystallization produced by heat alone; and second, a pneumatolytic, metasomatic or hydrothermal stage produced by the percolation of hot fluids.

The foregoing petrographical descriptions have served to show that both these types may be recognized at Hartley, together with a further change, namely, reaction or hybridization. Table I shows the chief petrographical evidence for the recognition of these processes among the main rock types.

Reference to this table shows that the chief petrographical reasons for the assumption that the hornblende-pyroxene-gabbros are hybrids are based on phenomena which might be attributed to reaction in the normal course of crystallization. There is evidence, however, that the rocks had solidified and become partly recrystallized before reaction took place. The reacting solutions, therefore, must have come from the quartz-mica-diorite magma. The hybrid origin is further supported by the field evidence, since the "reaction"-gabbros surround a partly recrystallized core of gabbro devoid of hornblende, and are themselves surrounded by the quartz-mica-diorites which are rich in hornblende. Chemical evidence also lends support to this conclusion.

The deuterically altered hornblende-gabbros, which occupy a small area in the centre of the Cox's River Intrusion, have suffered no thermal effects. They may represent, therefore, either a remnant of the original gabbro intrusion, that has been in no way affected by the quartz-mica-diorite, or the central portion of the original intrusion, which was still unconsolidated at the time of the later intrusion. It is evident, however, that reaction took place in the normal course of crystallization, and that this was followed by a deuteric period as an end-phase in the consolidation of the gabbro. The hornblende-gabbros were possibly a little less basic than the rocks that surrounded them; that is, as on Moyne Farm, the more acid rocks occupied the centre of the intrusion. The occurrence of slightly more acid plagioclase, and sometimes a little quartz and biotite in the hornblende-gabbros points to some differentiation having taken place in the original gabbro magma.

After this differentiation of the gabbro and after the rock had completely consolidated, with the possible exception of the central core, the mass was encircled by a quartz-mica-diorite magma, and partly metamorphosed.

It is evident that the first stage of metamorphism, that is, the thermal stage, was responsible for the partial recrystallization of the whole of the gabbro mass except the small central core, which either remained unaffected or was as yet unconsolidated. If the former be the case, then the thermal effect extended a distance of 10 to 30 chains from the contact.

Immediately following upon the recrystallization, and before the hydrothermal stage of metamorphism set in, a certain amount of reaction took place between the solid gabbro and the fluid quartz-mica-diorite, thus giving rise to the hornblende-pyroxene-gabbros or "reaction"-gabbros. It is significant that these rocks have been partly recrystallized, and always form an outer, though very irregular, border about the pyroxene-gabbros. Most of the rocks of this group appear to be of the nature of acidified gabbros, but one specimen (p. 132) might be termed more correctly a basified diorite. This rock contains idiomorphic brown hornblende and two generations of plagioclase, the later being the more acid and of an acicular habit. The larger felspar crystals and pyroxenes surrounded by reaction-rims of brown hornblende possibly represent the original constituents of a gabbro, with a grainsize of about 1 mm., which has been completely disrupted. The original minerals have been thus scattered and some solution of the basic material has taken place giving rise to a sufficiently basic liquid to produce brown hornblende on crystallization. The strewing of the original minerals has allowed space for the brown hornblende to take on an idiomorphic form. The acicular felspar possibly crystallized from the substance of the more acid magma, although its presence in the pyroxene places a grave objection in the way of this interpretation.

Reaction and the production of brown hornblende from pyroxene and plagioclase, together with the probable deposition of hornblende from the substance of the invading magma, apparently took place more readily along certain lines of weakness in the hornblende-pyroxene-gabbro, possibly owing to higher temperature conditions produced by the concentration and escape of volatile constituents. Vein-like segregations of hornblende and a mesostasis of slightly more acid material from the fluid magma were thus formed, giving rise to the hornblendites.

At certain localized points, possibly where there was an escape of volatile constituents, superheating occurred and the solid gabbro entirely or partly dissolved in the more acid magma, giving rise to diorite-gabbros and hornblende-gabbros. The former are basified diorites and the banded types point to a drawing out of the incompletely dissolved gabbro. The hornblende-gabbros represent acidified gabbros and bear a very close resemblance to those in the centre of the complex. In fact, it might be argued that the central mass represents a larger outcrop of these sporadically-distributed hornblende-gabbros, and just chances to occupy a central position. The central gabbros, however, show incipient recrystallization and are enveloped by the pyroxene-gabbros, which are free from the sporadically-distributed hornblende-gabbros. It would thus appear that the central mass antedated the quartz-mica-diorite invasion. The two hornblende-gabbros might be expected to have a similar composition, as the central gabbro possibly arose as the more acid differentiate of the original gabbro magma, whilst the scattered patches of hornblende-gabbro originated as products of the reaction between the more basic differentiates of this early magma, and a later more acid magma.

Whilst these processes were in progress, the quartz-mica-diorites were crystallizing. Near the outer margin the temperature was falling rather rapidly, and the composition of the magma constantly changing, as the highly-zoned felspars show. It is probable that the first consolidated layers formed a non-conducting envelope about the intrusion, and it is for this reason that the various processes of reaction and hydrothermal alteration have advanced so far.

Reference to Plate v shows that isolated patches of recrystallized pyroxene-gabbro occur within the quartz-mica-diorite and fairly close to the margin of the intrusion. These evidently represent fragments that were rifted off from the gabbro mass and made their way towards the margin whilst the quartz-mica-diorite magma was still fluid. They were thus recrystallized, but owing to their proximity to the contact they were caught up in the rapidly cooling and solidifying diorite and the temperature was not maintained for a sufficient length of time for reaction to take place. The occasional isolated patches of hornblende-pyroxene-gabbro evidently originated in a similar manner, but in this case temperature conditions favoured some reaction.

As an end-phase in the consolidation of the quartz-mica-diorite magma a period of deuteric activity set in. This is evidenced in the diorites by the presence of epidote, sericite, saussurite, (?)lawsonite, etc. Accompanying this autometamorphism of the quartz-mica-diorites, aqueous, aqueo-siliceous and other deuteric solutions made their way along lines of weakness in the gabbros, and the rocks were thereby hydrothermally altered. It might be noticed that the chief product of this stage of metamorphism is uralite, and it seems likely that the aqueous and aqueo-siliceous solutions that give rise to this mineral were more abundant, more active and more mobile than the other deuteric solutions, and were thus able to penetrate the neighbouring rocks.

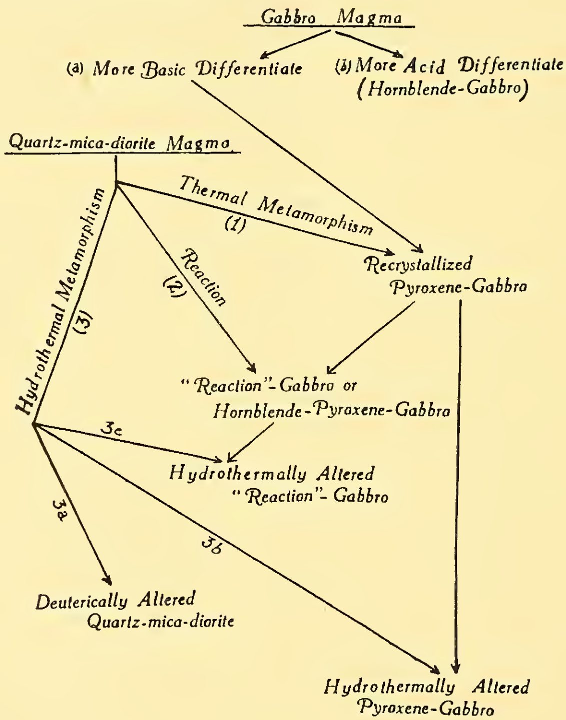


TABLE II.

Table II represents a diagrammatic attempt to show that the chief rock types have been produced as a result of differentiation followed by the three types of metamorphism due to the quartz-mica-diorite intrusion: (1) Thermal metamorphism; (2) Reaction; (3) Hydrothermal metamorphism.

The hedenbergite-bearing gabbros appear to have quite a different origin from the types discussed above, and seem to have resulted from the addition of lime and silica to the gabbro magma. Such a combination could occur only in a sediment, and the presence of abundant calc-silicate hornfelses in the aureole points to contamination by sediments.

ii. *Physico-chemical Discussion.*

The assumption that some of the Hartley rocks are hybrids calls for some justification on physico-chemical grounds.

It has been shown that field occurrence and petrography point to four groups of rocks of mixed origin:

(1) The hornblende-pyroxene-gabbros, which are apparently due to reaction between solid gabbros and the fluid quartz-mica-diorite magma, and therefore represent acidified gabbros. One specimen, described on pages 132 and 138, might be regarded as a basified diorite.

(2) The hornblendites, which are segregations of "reaction" brown hornblende that has crystallized in a mesostasis of more acid material.

(3) The isolated patches of hornblende-gabbros and diorite-gabbros, which appear to be true hybrids, and represent complete solution of the solid basic rock in the more acid magma.

(4) The hedenbergite-bearing gabbros that are apparently due to the assimilation of sediments.

It is obvious that different physical and chemical conditions were responsible for the formation of these different types, whose divers origins have already been discussed. It has been suggested that (1) and (2) are due to reaction, and (3) to solution, whilst (4) may be accounted for by the assimilation of sediments. It is now proposed to discuss the physico-chemical conditions responsible for (*a*) reaction, (*b*) solution, and (*c*) contamination by sediments.

(*a*) *Reaction or partial hybridization.*

Dr. N. L. Bowen (1922*b*) has shown "that the solution of a silicate in a magma is usually accompanied by a large absorption of heat, probably of the order of magnitude of the heat of melting".

Bowen has also shown that if the melting point of the solid phase be lower than that of the fluid in which it is immersed, complete solution will take place. As an example of this, he takes the case of a granite inclusion in a basaltic magma. The granite is supersaturated with all higher (i.e., more basic) members of the reaction-series (Bowen, 1922*a*) and complete solution will take place in the basaltic magma. If, however, a basic inclusion be immersed in an acid magma, the fluid can not dissolve it, but may react with it and convert it into such members of the reaction-series with which the fluid is saturated. It is evident, therefore, that without the aid of superheat a solid gabbro cannot go into solution in a diorite magma.

The basic felspars and the pyroxene of the recrystallized-gabbros at Hartley could not dissolve in the quartz-mica-diorite magma, but they were able to react with it and give rise to zoned and mottled felspar and reaction-rims of brown hornblende, since green hornblende and andesine are the members of the reaction-series with which the diorite magma was saturated.

Moreover, Bowen considers that the magma may not only react with solid gabbro, but may deposit, from its own substance, the minerals with which it is saturated. In the case of the hornblendites, which possibly represent segregations of the "reaction" hornblende along cracks in the gabbro, the borders of greenish hornblende and the acid mesostasis were probably deposited from the substance of the invading magma.

Bowen (1915, 1922*a*) has shown that reaction takes place in a magma during the normal course of crystallization, and as it will be shown below that the parent magmas at Hartley are consanguineous, these so-called partial hybrids might be regarded as normal differentiates of an original parent magma. The gabbros, however, were undoubtedly solid before the intrusion of the later more acid partial magma, and the progress of differentiation was thereby interrupted and physical conditions changed. H. H. Thomas and E. B. Bailey (1924) point out that an internal migrating partial magma, still in the fluid state, will react with an earlier separated solid phase, and they distinguish between this process and that of true hybridization when an independent magma acts upon an already consolidated rock. These authors also say, "It will be seen that the two processes have much in common, and in extreme cases the results may be indistinguishable". The Hartley rocks seem to be a case in point, but the evident temperature change rather favours their being called hybrids.

(*b*) *Solution.*

A complete solution has been postulated for the origin of the isolated outcrops of the hornblende-gabbro and diorite-gabbro, since the fabric of both is ophitic, the composition is intermediate between gabbros and quartz-mica-diorites and there is no evidence of recrystallization. Dr. Bowen admits the possibility of a complete solution of a basic rock in an acid magma where there is superheating, but points out that superheating is not a common occurrence.

It has already been indicated that the Hartley gabbros and diorites are comagmatic, and it is fairly evident that the gabbros were still hot and the surrounding country rocks considerably warmed up at the time of the quartz-mica-diorite intrusion. It is even conceivable that the diorites may have been injected at a temperature above that of the fusion point of the gabbros at the reduced pressure of their higher position in the earth's crust. The partial recrystallization of the gabbros, however, shows that this was not the case, but we can at least admit a temperature not far below the fusion point, and little superheat would be required to attain it. Moreover, when this temperature was acquired the heated country rocks would prevent a rapid dissipation. The extra heat required to raise the gabbros to the fusion point might be supplied by escaping gases, and the localized occurrence of the hornblende-gabbros and diorite-gabbros favours this explanation. Solution would possibly be aided by the high iron content of these rocks acting as a flux, and once solution had commenced no further superheat would be required, since, as indicated by Daly (1914), the experimental work of Petrasch and Doelter has shown that the melting point of a mixture of rocks of different composition is lower than that of either of the separate rocks.

The fact that both hornblende-gabbros and diorite-gabbros arose in this way points to different temperature conditions in different parts of the mass. The more basic hornblende-gabbros indicate that a greater proportion of gabbro went into solution, and it would thus seem evident that the temperature at which these rocks consolidated was greater than that at which the diorite-gabbros solidified.

The banded diorite-gabbros possibly represent the incomplete solution and softening and drawing out of the gabbros (Harker, 1904, p. 117) or else indicate an immiscibility of the liquid magmas.

(*c*) *Contamination by Sediments.*

Bowen and his co-workers at the Carnegie Institution (Bowen, 1922*b*) have shown experimentally that the addition of lime to a basaltic magma is exothermic, and no very great modification of the magma is possible without superheating. They show, however, that reaction may take place and that a more calcic plagioclase and pyroxene may result. This appears to be what has happened in the case of the hedenbergite-bearing gabbros at Hartley, and the quartz veins and interstitial quartz grains possibly represent assimilated quartz, which has readily dissolved in the basic magma and separated out as an end phase. Sphene has arisen in place of ilmenite as a result of the assimilation of lime.

The recent work of Dr. C. E. Tilley in Ireland (1929, 1931) has shown that very important modifications of the magma actually do occur, but he agrees with Dr. Bowen in regarding the effects as limited, and this is again borne out by the very localized outcrops of these contaminated rocks in the Cox's River Intrusion.

iii. *Origin of the Ellipsoidal Bodies.*

Four possible explanations of the origin of these bodies suggest themselves: (1) An original amygdaloidal or miarolitic structure. (2) An original orbicular structure. (3) Contamination followed by recrystallization. (4) Recrystallization of original zoned hornblende crystals.

Dr. Harker (1904, p. 51) has shown that comparable structures among the recrystallized basalts of Skye represent originally zoned infillings of amygdules, but the sporadic distribution and the nature of the rock tends to discount such an origin in the case of the Hartley ellipsoids.

In considering the second possibility it is pertinent to summarize the chief characteristics of an orbicular structure (Lawson, 1904; Iddings, 1909; Cole, 1916).

1. The orbicular facies of any rock mass is confined to a definite area which grades out into the normal rock. The orbicules are not sporadically scattered through the normal facies of the rock.

2. The distances between the centres of these bodies are fairly uniform.

3. The orbicules are usually, though not always, spheroidal.

4. They are usually large, the size being often 9 cm. to 10 cm., or even larger.

5. There is nearly always a distinct radial arrangement of the constituent minerals.

6. The orbicules show concentric zones consisting either exclusively of a single mineral or of a certain definite mineral assemblage.

7. The centre of the spheroid is usually slightly coarser in grainsize than the zone surrounding it.

8. The centre usually consists of, or is very rich in, felspar.

With regard to the Hartley gabbros the distribution of the rocks containing these bodies is somewhat sporadic, although their occurrence always seems to be confined to the north-western part of the mass (see Plate v). Moreover, the number of bodies in a single slide is very variable, showing that they are unequally spaced. Again it is evident that the bodies in the Hartley gabbros are ellipsoids, never spheroids; and their size never exceeds more than 10 mm., that is, they are about one-tenth the size of a normal orbicule. A parallel arrangement has been noted in a few sections, but never a radial, and moreover, the parallelism is not always present. The last three conditions tabulated are certainly fulfilled by the Hartley ellipsoids, but the bulk of evidence tends to show that they do not represent an original orbicular structure.

Orbicular rocks exhibiting some rather remarkable features have recently been described from Alderney by S. R. Nockolds (1931) and A. E. Mourant (1932).

The following is a summary of their work and conclusions:

1. The orbicules may be widely scattered.

2. Though apparently fairly uniform for any particular locality the size of the orbicules may vary from about 20–40 mm. (Nockolds) to about a foot (30 cm.) in length (Mourant).

3. The orbicules are usually flattened spheroids.

4. They are associated with basic xenoliths of a comparable size.

5. The radial structure is absent or poorly developed.

6. The orbicules are slightly different in mineral composition from the normal rock enclosing them, and bear evidence of having suffered hydrothermal action.

7. The orbicules are surrounded by material which is coarser in grain than the normal rock and resembles the orbicule more closely in mineral composition.

8. Both authors agree that the orbicular structure is due to contamination.

The small size of the orbicules examined by Nockolds, the shape, and the frequent absence of radial structure is in accord with the Hartley type, but at Hartley there is evidence neither of a mineralogical difference between the ellipsoids and the enclosing rock, nor of the presence of assimilated xenoliths. The Hartley ellipsoids might be accounted for, however, by postulating sporadically-distributed xenoliths of number insufficient to produce an orbicular structure. If these were completely assimilated by the gabbro, it is possible that minor mineralogical and textural differences might be obliterated by recrystallization. The fact that the ellipsoids are completely granoblastic whilst the remainder of the rock shows relict structures, however, presents a difficulty in this interpretation.

The possibility of the ellipsoids being original zoned hornblende crystals may now be considered.

1. The sporadic distribution is not altogether out of harmony with this view.

2. The ellipsoids occur only in the recrystallized types, although this is no very definite criterion, since they are never abundant and only a few specimens of the unaltered gabbros are available. Furthermore, the unaltered types may represent a different facies.

3. If a section of an ellipsoid be viewed macroscopically against a light background, the shape suggests that of a section of hornblende.

4. It is believed that hornblende was an original constituent of the gabbros, and is now represented by granules of augite and hypersthene, and the basic outer zones of the plagioclase. It is possible, therefore, that large zoned hornblende crystals may have broken down in similar fashion and that the various mineralogical zones of the ellipsoid correspond to composition zones in the original hornblende crystal.

5. There is some chemical evidence for this assumption (p. 152), although it is difficult to account for the textural differences of the various zones.

6. The presence of comparatively large stable augite crystals suggests that the original rock may have been porphyritic in ferromagnesian minerals, and that the recrystallization of augite alone was not responsible for the present mineral assemblage in the recrystallized gabbros. Moreover, the size of the smaller ellipsoids is quite comparable with that of the augite crystals, although no actual hornblende phenocrysts have been noted in the few unaltered hornblende-gabbros examined. Text-figure 2 shows a large augite crystal surrounded by a

reaction-rim of hornblende and on recrystallization this would probably produce zoned mineral assemblages.

7. The parallel arrangement, which is not present in every section, may represent a particular direction in the original crystal.

8. The cross-like arrangement of the coarser central zone in one of the ellipsoids may represent a kind of original hour-glass structure in the hornblende.

In many respects this last explanation of the origin of the ellipsoids seems to be the most likely, but at the same time the possibility of contamination followed by recrystallization cannot be entirely dismissed.

iv. *Consanguinity of the Parent Magmas.*

The consanguinity of the gabbros and quartz-mica-diorites is indicated by three criteria, namely, field relations, mineralogical constitution and chemical composition.

(1) *Field Relations.*—In the opinion of Dr. Harker (1904, p. 169) the very intimate association of two rocks in the field is indicative of their close genetic relation. The Hartley rocks are closely associated both in time and space. The fact that the gabbros were still at a high temperature, and the central core possibly unsolidified when the diorites were injected points to their proximity in "time"; and that the second intrusion encompassed the first shows their relation in "space".

(2) *Mineralogical Constitution.*—The foregoing descriptions of the rocks in this paper, together with those published in 1931, have served to indicate that there is a close mineralogical relation. The unaltered core of hornblende-gabbro at the centre of the Cox's River Intrusion compares closely with the intermediate types that have suffered no metamorphism. In all these types hornblende is the dominant femic mineral, and in the recrystallized gabbro it seems likely that the greater part of the rhombic pyroxene has been produced as a result of the thermal metamorphism of brown hornblende. Biotite is also very characteristic of this rock series and is found in small quantity in the unaltered hornblende-gabbros.

(3) *Chemical Composition.*—Reference to Table III will show that the composition of the recrystallized pyroxene-gabbro (column iii) is very close to, though slightly more basic than, that of the hornblende-pyroxene-gabbro (column iv), which was erroneously believed to represent the composition of the original gabbro magma (Joplin, 1931). It has already been indicated that the pyroxene-gabbros have eucritic affinities, and this finds chemical support in the analysis of the recrystallized pyroxene-gabbro in column ii, which represents a slightly more leucocratic phase.

Although the writer has already shown (1931) the relation of the hornblendite, hornblende-pyroxene-gabbro, diorite-gabbro and the Cox's River type of quartz-mica-diorite to the intermediate and acid members of the series, it is deemed necessary to repeat the analyses of these rocks (Table III), and to place the recently analysed recrystallized pyroxene-gabbros on a variation-diagram with those types that have suffered no apparent hybridization (Text-fig. 3). This diagram, therefore, represents the serial differentiation of the magma in an intercrustal reservoir and a simple secondary differentiation of the partial magmas. It is evident that this variation-diagram has affinities with the linear type. Some smoothing of the curves has certainly been necessary at the basic end, but from this it is apparent that there has been secondary differentiation among the gabbros

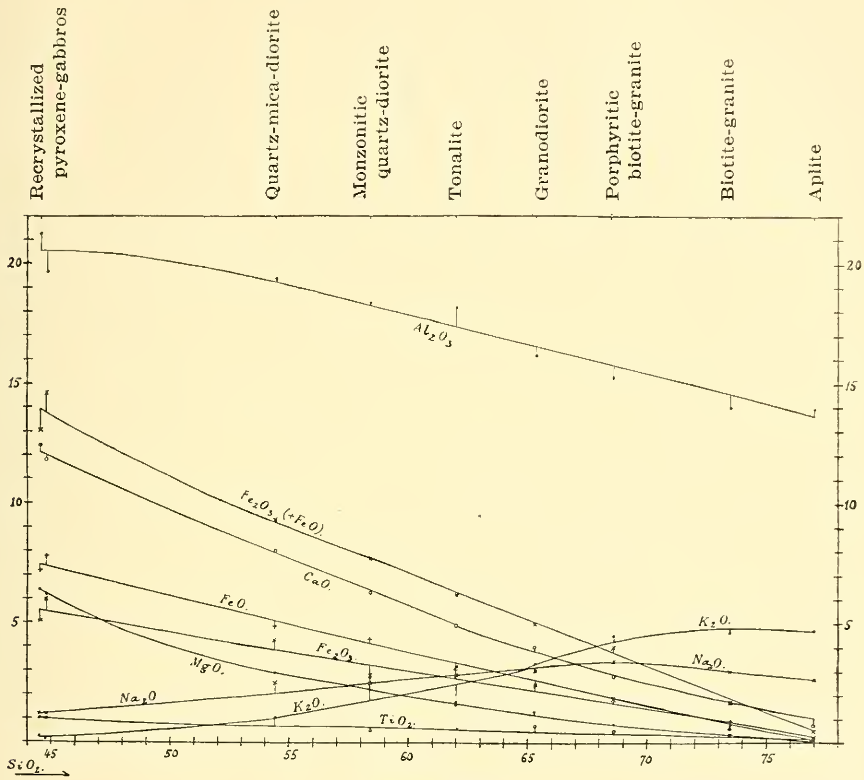
TABLE III.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.	XIII.
SiO_2	41·82	44·52	44·79	45·31	46·49	52·41	54·37	58·37	62·06	65·33	68·60	73·51	76·94
Al_2O_3	11·79	21·32	19·56	19·39	19·22	20·11	19·64	18·38	18·25	16·20	15·33	14·03	13·98
Fe_2O_3	8·64	5·08	6·01	5·33	6·68	4·18	4·30	2·80	2·91	2·43	1·92	0·69	0·18
FeO	11·68	7·19	7·79	7·81	6·02	5·59	4·87	4·43	2·94	2·38	1·85	0·91	0·27
MgO	8·68	6·41	6·16	6·93	5·89	4·12	2·94	2·79	1·71	1·28	0·81	0·38	0·06
CaO	12·14	12·44	11·81	11·67	10·88	9·06	8·07	6·29	4·90	4·02	2·78	1·69	0·78
Na_2O	0·53	1·25	1·21	1·22	2·16	2·28	2·55	2·52	3·12	3·02	3·38	3·03	2·68
K_2O	0·25	0·15	0·06	0·35	0·65	0·88	1·01	2·56	1·61	3·28	4·52	4·58	4·67
H_2O + ...	0·47	0·37	0·64	0·69	0·96	0·36	0·96	0·56	1·34	0·58	0·50	0·20	0·39
H_2O −	0·16	0·06	0·10	0·08	0·17	0·16	0·11	0·16	0·16	0·10	0·11	0·18	0·11
TiO_2	2·26	1·04	1·14	1·33	0·92	0·78	1·14	0·52	0·60	0·72	0·51	0·45	0·16
P_2O_5	0·42	abs.	0·18	0·31	0·40	0·32	0·34	0·26	0·24	0·22	0·22	0·05	0·02
MnO	0·20	0·09	0·15	0·17	0·20	0·19	0·07	0·06	0·09	0·03	0·04	0·01	tr.
CO_2	0·53	tr.	tr.	tr.	tr.	tr.	—	—	—	—	—	—	—
Total	99·55	99·92	99·60	100·59	100·64	100·46	100·37	99·70	99·93	99·59	100·57	99·81	100·24
Specific Gravity ..	3·000	3·050	3·055	3·004	2·967	2·836	2·861	2·807	2·764	2·742	2·703	2·658	2·603

I. Hornblendite. II. Recrystallized Pyroxene-gabbro (leucocratic type). III. Recrystallized Pyroxene-gabbro (normal type). IV. "Reaction"-gabbro (previously called Pyroxene-gabbro). V. Diorite-gabbro. VI. Quartz-mica-diorite (Cox's River type). VII. Quartz-mica-diorite (Moyne Type). VIII. Monzonitic Quartz-diorite. IX. Tonalite. X. Granodiorite. XI. Porphyritic Biotite-granite. XII. Even-grained Biotite-granite. XIII. Aplite.

With the exception of II and III, which are published for the first time in this paper, these analyses appear in PROC. LINN. SOC. N.S.W., Vol. lvi, Pt. 2, 1931, p. 53.

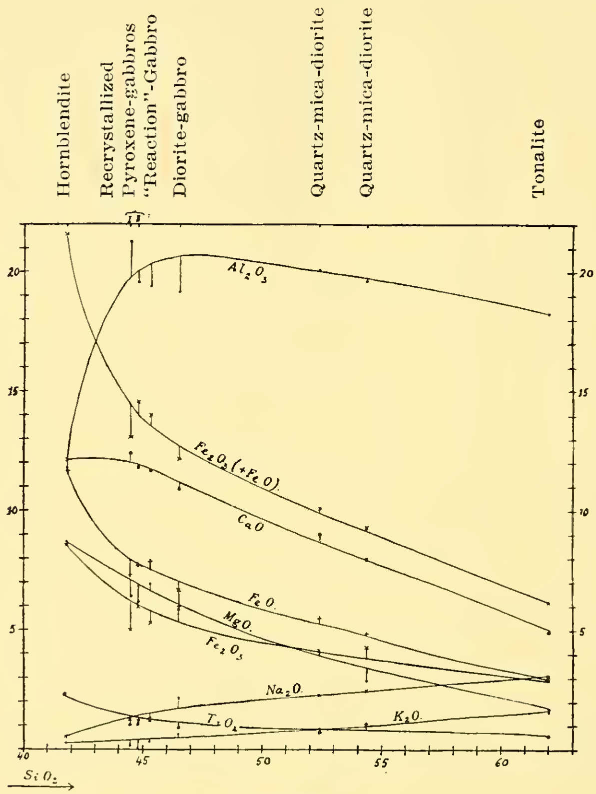
themselves. If reference be made to a variation-diagram of any typical calcic province plotted in such a way that the silica percentages are used as abscissae and the other oxides as ordinates, it will be seen that the oxides, with the exception of the alkalis, usually fall upon straight lines when the silica percentage is above 52. According to Holmes (1921) the Hartley series belongs to a calcic complex, since the lime curve bisects the vertical between the alkali curves at a silica percentage of 66½, although it will be shown later that this series



Text-fig. 3.

exhibits certain peculiarities. The fact that the curves are approximately straight between 54·37% and 76·94% of silica is to be expected, but that they continue to remain fairly straight as far as a silica percentage of 44·52 calls for comment. Harker (1909), in giving a mineralogical interpretation of a sub-alkaline variation-diagram, has pointed out that anorthite contains 37% of alumina and the other felspars less. As the Hartley gabbros, particularly the leucocratic types, have eucritic affinities the alumina percentage is considerably higher than that of normal gabbros with a similar silica percentage. The alumina, therefore, follows a gentle curve towards the quartz-mica-diorite instead of abruptly rising. Similarly since there is an antipathetic relation between Al_2O_3 and Fe_2O_3, the iron oxides, instead of abruptly descending, come down on a very gentle curve. It is obvious that, had the leucocratic phase of the gabbro, with its high alumina and low iron oxides, been considered alone, the alumina and iron oxide curves could have been drawn as straight lines.

A second variation-diagram (Text-fig. 4) has been plotted to show the relations of the hybrid rocks to the parent magmas. The tonalite is included in this diagram since it is a differentiate of the Moyne quartz-mica-diorite, whose composition is possibly close to that of the parent quartz-mica-diorite magma. It will be seen that with very little smoothing the curves are typical of the basic



Text-fig. 4.

end of a calcic or sub-alkaline series. The fact that the secondary differentiation of the gabbros is readily smoothed out and that the hybrids take their place upon the normal curves further supports the genetic relation of the two reacting types and emphasizes the slight distinction between normal differentiates and hybrid rocks arising from cognate parents, when free diffusion has been able to take place.

It seems evident that at least two processes operated in the differentiation of the Hartley series—gravity separation and assimilation. The writer has previously indicated (1931) that there were possibly three main acts of intrusion from an intercrustal reservoir—(1) gabbro; (2) quartz-mica-diorite; (3) granite; and presumably these three types are due to gravity separation. The results recorded in the present paper indicate that the series between the gabbro and quartz-mica-diorite is the result of hybridization; thus assimilation, though it be concerned with comagmatic types, is an important factor in giving rise to this rock series.

In an endeavour to show that differentiation does not always take place as a result of the gravitational separation and the sinking of crystals, C. Fenner (1926) has reviewed the various theories of differentiation and concludes that a linear variation-diagram is indicative of the operation of a process other than gravity-sinking.

With regard to the Hartley series, the types supposed to be due to gravity separation alone readily take their places upon a somewhat linear type of variation-diagram, and those that are proved to be hybrids fall upon curves in direct contrariety to the arguments of Fenner. It is true that the gabbros have suffered secondary differentiation and, had the normal type alone been plotted, the linear relation for the basic end of the series would not be so apparent. It has been pointed out, however, that the linear type of diagram is not uncommon for a calcic series with a silica percentage above about 52. This being the case, must the differentiation of all such series be attributed to some cause other than the gravity separation of crystals? There seems to be a danger in comparing the diagram of an actual rock series with one of an ideal case such as the diopside-albite-anorthite series (used by Fenner), which has been derived experimentally under laboratory conditions. The writer does not feel competent to discuss this question, but at the same time is not prepared to attribute the differentiation of the whole of the Hartley series to assimilation, or to some process other than gravity separation.

An examination of Table III and of Text-figures 3 and 4 shows that the Hartley series have certain chemical peculiarities, and in some cases these can be interpreted mineralogically. It will be noticed that alumina is exceptionally high throughout the series, that the potash curve crosses that of soda at a silica percentage of about 66 instead of in the more normal position of about 68%, and that in the gabbros potash is extremely low. These facts can possibly be explained by the eucritic affinities of the gabbros and by the high biotite content of most of the other members of the series. The alumina would be contained mainly in the anorthite-molecule in the gabbros, and with the coming in of potash, in the more acid rocks, would enter into the biotite-molecule. Biotite is the chief ferromagnesian mineral in the acid rocks of this series and in the intermediate types it is equal to or even greater than hornblende, whilst it is present as an accessory in some of the deuterically altered hornblende-gabbros. Titania is rather low in the gabbros, and Holmes (1921, p. 459) has pointed out that there is an antipathy between this oxide and normative anorthite.

Reference to other typical calcic series shows that magnesia is usually higher than ferrous oxide, but at Hartley the reverse is the case. Moreover, soda is comparatively high for a normal sub-alkaline complex. Washington (1915) has shown that "soda not uncommonly tends to vary with the iron oxides, while potash shows similar relations to magnesia". The first statement seems to be true for the Hartley rocks, but the relation between potash and magnesia does not hold.

Besides the high ferrous oxide it will be noticed that ferric oxide is unusually high and often approximately equal to the ferrous oxide. This can possibly be explained by deuteric alteration, which is common to most members of the series.

v. *Chemical Changes involved during Hybridization and Metamorphism.*

It is not unreasonable to assume that the quartz-mica-diorites on Moyne Farm and on Cox's River originated from the same partial magma, and were originally of the same composition. The Moyne magma differentiated *in situ*, giving rise to a central mass of tonalites and an outer fringe of more basic quartz-mica-diorite. The original partial magma was, therefore, more acid than the Moyne quartz-mica-diorite, since this latter represents the original type depleted of some of its more acid constituents by differentiation. Assuming this to be the case, it is evident that the Cox's River type has been still more basified, although no acid differentiate is apparent. The basification has probably been effected by assimilation of gabbro, and the diorite is thus a hybrid.

According to Nockolds (1931) "reciprocal reaction is the very essence of contamination", but unfortunately this is impossible to show in the case of the Hartley series, since the true composition of the reacting quartz-mica-diorite is unknown. Reference to Text-figure 4 will show that the hybrid gabbro and diorite are intermediate in composition between the recrystallized gabbro and the Moyne diorite and, although the Hartley analyses are not altogether suitable for such a comparison, the writer should like to point out the danger of a direct comparison as employed by Foye (1915), Read (1923) and Nockolds (1931). Merrill (1906), Ransome (1911) and Browne and White (1926, 1928) have already indicated the inaccuracies arising out of such a comparison, and have shown that a true comparison can be made only by assuming that some standard constituent has remained constant, or by comparing unit volumes of the rocks. By the direct method unit weights are compared and if the two rocks differ in specific gravity and porosity, then the comparison is made between unequal volumes of the reacting rocks. Ransome (1911) has discussed this at some length, and explains that if, for example, one rock be twice the specific gravity of another, then by the direct method a unit volume of one rock is compared with half that of the other. It is evident from this extreme case that such a comparison is invalid.

Unfortunately the comparison of equal volumes can be made only between two rocks that have remained solid during reaction. Thus the Hartley gabbros, the parent and the hybrid, may be compared, since the gabbro was a solid and the "reaction"-gabbro did not crystallize from solution but was produced as the result of reaction between the magma and *solid* gabbro. Even if the true composition of the parent diorite were known, however, it could not be compared with the hybrid diorite, since the latter crystallized from solution, and it is impossible to say what volume of the fluid magma reacted with the solid gabbro to form the hybrid diorite magma.

Table IV shows a comparison between equal volumes of the recrystallized gabbro and the "reaction"-gabbro. Both analyses have been re-calculated to 100, so that equal weights may be the basis of the calculation. It is doubtful whether this is valid, since it is an assumption that the experimental error is proportionally distributed whilst in reality it may have occurred in the estimation of a single constituent (Washington, 1919, p. 26). This will serve, however, as a reasonable basis for an approximate comparison. In the hybrid as compared with the parent gabbro the specific gravity has been decreased by about 1·6% as the result of contamination and the analysis of the parent gabbro has therefore been re-calculated (column E) so that its sum is about 98·4 instead of 100.

TABLE IV.

	A.	B.	C.	D.	E.
SiO_2	44·79	45·31	44·97	45·05	44·21
Al_2O_3	19·56	19·39	19·64	19·28	19·31
Fe_2O_3	6·01	5·33	6·03	5·30	5·93
FeO	7·79	7·81	7·82	7·76	7·69
MgO	6·16	6·93	6·19	6·89	6·08
CaO	11·81	11·67	11·86	11·60	11·66
Na_2O	1·21	1·22	1·22	1·21	1·21
K_2O	0·06	0·35	0·06	0·34	0·06
H_2O + ...	0·64	0·69	0·64	0·69	0·64
H_2O −	0·10	0·08	0·10	0·08	0·10
TiO_2	1·14	1·33	1·14	1·32	1·14
P_2O_5	0·18	0·31	0·18	0·31	0·18
MnO	0·15	0·17	0·15	0·17	0·15
Total	99·60	100·59	100·00	100·00	98·36
Specific Gravity ..	3·055	3·004			

A. Recrystallized Pyroxene-gabbro (Normal Type).
B. "Reaction"-gabbro.
C. Analysis A re-calculated to 100.
D. Analysis B re-calculated to 100.
E. Analysis A re-calculated as explained in text.

Columns D and E, therefore, represent unit volumes of the two rocks, and if these be compared certain slight gains and losses are apparent. Differences less than 0·10% have not been taken into account as it is possible that such are due to experimental error. It is evident that the gabbro has gained SiO_2, MgO, K_2O, TiO_2 and P_2O_5 from the diorite magma, and has lost Fe_2O_3.

An examination of a series of pyroxene and amphibole analyses (Iddings, 1911; Clarke, 1910) shows that silica, magnesia and potash are higher in the amphiboles, so it seems possible that these additions from the diorite magma entered into the composition of the "reaction"-hornblende.

The chemical changes brought about by metamorphism may now be considered.

The chief mineralogical changes are the production of rhombic pyroxene and more calcic felspar in the recrystallized gabbros, and the formation of uralite, etc., in the hydrothermally metamorphosed types.

The original mineral composition of the recrystallized gabbros is somewhat doubtful. The central core of the Cox's River Intrusion certainly seems to be a more acid differentiate, and in this rock hornblende is the dominant ferromagnesian mineral, so it is likely that this amphibole occurred in the outer slightly more basic differentiate. The presence of apparently unaltered augite in some of the recrystallized gabbros, however, indicates that there was at least some monoclinic pyroxene originally present, and that this was stable under the thermal conditions. It is also probable that some of the hypersthene is primary, although the greater part appears to be the product of recrystallization. If the primary augite was stable, then brown hornblende is indicated as the mineral that gave rise to basic plagioclase and secondary hypersthene, augite and iron ores.

C. E. Tilley (1921), F. L. Stillwell (1923) and W. R. Browne (1927) have shown that similar changes occur in the breaking down of pyroxenes in metamorphosed basic igneous rocks.

The following equation illustrates the breaking down of the hornblende as observed at Hartley:

$$2\left\{\begin{matrix} m\ CaMg_2(SiO_3)_3 \\ MgAl_2SiO_6 \end{matrix}\right\} = \left\{\begin{matrix} (2m-1)\ CaMg(SiO_3)_2 \\ MgAl_2SiO_6 \end{matrix}\right\} + 2(m+1)MgSiO_3 + CaAl_2SiO_6$$

Hornblende Augite Hypersthene Anorthite

In the case of brown hornblende the high iron percentage would be evidenced by a discharge of iron ores, and such are present in association with the pyroxenes of the gabbros at Hartley.

The zoned ellipsoids that have been described in the present paper (p. 143) may thus be accounted for by the breaking down of zoned hornblende consisting of iron-rich, magnesia-rich and alumina-rich shells.

The chief change produced by hydrothermal metamorphism is the production of uralite from pyroxene. This was probably effected by the action of superheated steam and hot aqueo-siliceous solutions. Deuteric activity among the quartz-mica-diorites has resulted in the production of lime and potash minerals. It is possible that muscovite is the result of pneumatolysis connected with the granites, though it is usually associated with deuteric minerals and may be paragenetic with them. Only one definite example of pneumatolytic action has been noted, where a little pyrites and tourmaline occur in a hornblende-gabbro. The addition of lime (from the gabbros) to the quartz-mica-diorite magma would possibly account for a late concentration of potash, with the formation of deuteric lime and potash minerals. The occasional sodic borders of the hornblende may be accounted for similarly.

vi. *Clearing and Clouding of the Felspar.*

Apart from the clouding of the felspar due to deuteric products, two types of alteration have been noted, namely a greyish clouding produced by minute inclusions, and a clearing accompanied by tiny granular inclusions either zonally arranged or centrally placed.

A. G. McGregor (1931) has discussed the phenomena of clouding and recognizes two types—a brown clouding due to the presence of ultramicroscopic inclusions, and a grey turbidity produced by tiny rod-like or hair-like inclusions of iron ores. Both types he ascribes to metamorphism, but considers that the felspar showing the greyish clouding has suffered a slightly higher grade of thermal metamorphism. Of the tiny granular inclusions he makes no mention, but states that under the grade of metamorphism which converts amphiboles into pyroxenes and renders labradorite unstable, the felspar is perfectly clear.

The greyish clouding of the felspar has been observed in several of the Hartley types—in some of the rocks that have suffered reaction and in some of the hydrothermally metamorphosed gabbros.

The cleared felspar with the accompanying tiny granules occurs in the recrystallized gabbros, but the felspar which is quite granular, and has evidently suffered complete recrystallization, is unaccompanied by granules. In some instances both greyish clouding and granules are present in the partially recrystallized felspar.

The writer has had the opportunity of examining a number of thin sections from various localities, exhibiting these phenomena, and it is pertinent to make brief reference to them.

A collection of metamorphosed dolerites from Broken Hill, kindly lent by Dr. W. R. Browne, contains perfectly limpid felspar crowded with granules of pyroxenes and brown hornblende, that are distinctly larger than those observed in the Hartley rocks. According to Dr. Browne (1927) the granules are sometimes so numerous that the felspar is rendered a grey colour, but it might be pointed out, however, that this grey colour is quite distinct from the grey cloudiness previously referred to, and that in this case the granules are easily distinguished as such. In some of the felspar of these rocks the aggregate of inclusions is of greater bulk than the thin outer rim of clear felspar. The Broken Hill dolerites exhibit blastophitic and granoblastic structures, and those felspars that are completely recrystallized and show no relict lath-habit are perfectly clear and free from inclusions. The femic minerals in these rocks consist of pyroxenes, brown hornblende, olivine and iron ores, and the ferromagnesians are heavily schillerized.

Another interesting collection of microsections was kindly lent by Mr. T. Hodge-Smith of the Australian Museum. These rocks were collected by Mr. Hodge-Smith in the Hart's Range, Central Australia, and appear to represent highly metamorphosed dolerites. Several phenomena are represented in the felspar of these rocks. As in some of the Hartley gabbros the granular, recrystallized felspar is quite clear and free from inclusions; other rocks partly recrystallized contain granular femic minerals indenting the partly granoblastic felspar, and in this case the felspar shows clearing with tiny granular inclusions or regularly arranged colourless or brown plates similar to schiller inclusions. Moreover, the "schiller" and granule-bearing felspar is usually accompanied by schillerization of the ferromagnesian minerals. Many of these rocks contain felspar that is clouded, and the grey clouding commonly accompanies the granules or schiller inclusions. Green hornblende replacing original pyroxenes is the most abundant femic constituent of these rocks.

Felspars showing colourless or brown schiller plates and, in the opinion of W. N. Benson (1910), negative crystals, are present in some of the very basic gabbro xenoliths from the Dundas volcanic neck, and here again the accompanying pyroxenes are usually heavily schillerized.

H. H. Thomas (1924) has also described gabbro xenoliths from Mull containing cleared felspar with granular inclusions.

A. Harker (1904) has described metamorphosed basalts from Skye showing this feature, and the writer has had an opportunity of examining a collection of these slides in the Geology Department of the University of Sydney.

McGregor (1931) cites a metadolerite from Eyre's Peninsula, South Australia, as an example showing cloudy felspar, and the present writer has been able to examine two microsections from this locality. There appear to be two types of alteration present—a clearing accompanied by granular inclusions and a clouding. Dr. C. E. Tilley (1921), in describing these rocks, refers to both of these phenomena, and McGregor groups them together under "clouding". According to Dr. Tilley, the granules are present only in the relict felspars, whilst those that are completely recrystallized are quite limpid. These rocks also contain schillerized ferromagnesians—brown hornblende, augite and hypersthene.

A search of the literature dealing with this subject shows that there is much confusion in the terminology. Some of the Scottish geologists refer to turbidity, others to schillerization, and McGregor, who has examined many of the Scottish rocks, is convinced that the phenomena described by these terms are identical with what he himself terms clouding. The present writer has compared plates of the Scourie dyke rocks (Teall, 1885, 1888) and examined sections of the Malchite and Orbite from Melibocus, Odenwald, referred to by McGregor, and is satisfied that the clouding described by McGregor is similar to that which is found in the Hartley rocks.

Excellent examples of the brown clouding have been observed in a section of the Odenwald gabbro, and in a uralitized dolerite from Broken Hill (Browne, 1922). Other evidence shows that both these rocks have suffered only a low grade metamorphism.

The brief descriptions given above together with the detailed petrography of the Hartley rocks points fairly conclusively to there being a relation between the size of the inclusions and the grade of metamorphism—the higher the grade the larger the inclusions. It would seem, therefore, that "clearing-with-inclusions" and "clouding" are essentially the same phenomenon, the fundamental difference being the degree of metamorphism suffered by the felspar. It has been pointed out that McGregor has observed this with regard to the grey and brown clouding and it would seem that clearing accompanied by granules or schiller plates belongs to the higher grades of thermal metamorphism, whilst the clear felspar unaccompanied by inclusions occurs when the grade of metamorphism has been high enough to cause complete recrystallization of the felspar. It is pertinent to note that the cleared felspar with granular inclusion is contained in rocks that bear other evidence of a high grade thermal metamorphism. There is often field evidence for this assumption, as well as the petrographic evidence of a partial granoblastic structure, a preponderance of pyroxenes over amphiboles and a marked development of rhombic pyroxene (Tilley, 1923). Sometimes, as in the Broken Hill and Eyre's Peninsula dolerites, brown hornblende is the most abundant femic mineral and this indicates a high grade thermal metamorphism under "wet" conditions.

When both clearing and clouding are present, as in the rocks from Eyre's Peninsula, the Hart's Range and Hartley, there is some doubt as to whether the rocks represent an intermediate grade of metamorphism or whether one grade has been superimposed upon another. From a consideration of the other evidence it seems certain that at Hartley, at all events, the weaker grade has followed upon an earlier high grade of metamorphism. The field evidence and the microscope examination point to an earlier partial recrystallization of some of the Hartley gabbros, followed by either reaction or hydrothermal metamorphism under low grade conditions. With regard to the Hart's Range rocks, the present writer knows nothing of their field-occurrence, but the presence of green hornblende and uralite wrapping partly recrystallized felspar crystals is certainly not contrary to the assumption that a high grade metamorphism was followed by one of lower grade. In the two Eyre's Peninsula slides examined, there is no evidence for assuming two grades of metamorphism, but Dr. Tilley himself states that the rocks have suffered a high grade thermal metamorphism and other changes during its decline (Tilley, 1921, pp. 117, 121, 125). The writer would suggest that the slight clouding of the felspar might be attributed to this latter period.

With regard to a discussion on the origin of these phenomena, many difficulties present themselves. It is obvious that iron oxides and/or magnesia are necessary for the formation of the inclusions, whether they be ultramicroscopic or comparatively large as in the Broken Hill dolerites, and that the amount of available material, besides the grade of metamorphism, possibly influences the size of the inclusions. It would also seem that magnesia enters into their composition only under the higher grade conditions.

Four possible explanations of the origin of the inclusions suggest themselves: (1) Oxides held in solid solution in the original felspar. (2) Breaking down of original inclusions in the felspar. (3) Addition of material from some external source. (4) Previous alteration of the felspar.

McGregor has discussed this question and concludes that the iron and/or magnesia are constituents of the original felspar. He states that the clouding is confined to the more basic zones of the felspar, and that analyses of plagioclases show that small quantities of these oxides are present in the more calcic end-members of the series. In the felspar of the Hartley rocks, however, clouding quite frequently occupies the more acid zones, and may be confined to certain twin lamellae of the felspar, so it is evident that McGregor's conclusions on this point are not fully justified. Moreover, little reliance can be placed on chemical analyses of plagioclases when such small amounts of "foreign" oxides are involved, as it is impossible to free the felspar from original minute inclusions.

The schiller plates in the Hart's Range and Dundas rocks certainly suggest the squeezing out of material held in solid solution, but the amount of material held in this way must necessarily be small, and it is difficult to account for the numerous, comparatively large granules in the felspar of the Broken Hill dolerites. Again, if clouding be superimposed upon granules, as suggested above, it is difficult to account for sufficient material for the formation of both, since there appears to be no diminution of either when the two phenomena are present together.

If the material be derived from original inclusions, it would seem certain that, under the low grade conditions, instead of clouding, a preliminary breaking down of the original inclusions would be noticed.

That the material is derived from an external source seems out of the question, since, in those Hartley types that have suffered the greatest deuteric or hydrothermal alteration, there is little or no clouding present. Besides this, it is evident that the hydrothermal solutions have produced alteration phenomena of a different type—saussuritization, epidotization, etc. In accounting for schiller inclusions, Judd (1885) ascribed them to percolating solutions under very deep-seated conditions.

McGregor has considered the possibility of an earlier alteration of the felspar, and his Ayrshire work (1930) has led him to the conclusion that only those parts of the felspar that were originally fresh are now clouded. The present writer feels that the same can not be said of the Hartley felspars. It is obvious that most of the Hartley types (Joplin, 1931) have suffered some deuteric alteration, and that the unmetamorphosed hornblende-gabbro in the centre of the Cox's River intrusion has been similarly affected; thus it would be too much to assume that the rocks now represented by the recrystallized pyroxene-gabbros have not also suffered from previous deuteric activity.

It might be pointed out in conclusion that all the examples exhibiting these phenomena, that have been discussed above, are basic rocks, and such types are very prone to deuteric alteration.

Summary and Conclusions.

It has been shown that an earlier partial magma of gabbro differentiated, giving rise to a slightly more acid core. The whole was then enveloped by a ring-like intrusion of a later, more acid, partial magma of quartz-mica-diorite, and the gabbros have thereby suffered three types of metamorphism: (1) Thermal metamorphism. (2) Reaction or partial hybridization. (3) Hydrothermal metamorphism.

It has also been shown that the gabbro and quartz-mica-diorite magmas are consanguineous, and that the rock types arising from the reaction of the one upon the other readily find a place upon a variation-diagram which is typical of a normal calcic series. The close connection between hybridization and the internal migration of magmas has been commented upon (p. 142), and it is assumed that the Hartley rocks are hybrids, since the recrystallization of the gabbros evidences an appreciable rise of temperature, whilst reaction, in the normal course of differentiation, necessitates no such change.

It has been shown, therefore, that assimilation, as well as gravity separation, has been an important factor in giving rise to the Hartley series.

On account of the close resemblance of the normal differentiates and the hybrids arising from cognate parents, the writer concludes that a careful search will reveal evidences of similar hybridization in other apparently normal rock series—particularly among the basic members of the series. If such can be shown, a strong case is made for assimilation as an important factor of differentiation. At Hartley the recrystallized-gabbros gave the clue to this interpretation, and it has been possible to trace all gradations from one type into another. When, however, the earlier intrusion is represented only by a very small outcrop, most of the evidence may be obliterated.

In the present paper it has been suggested that the tiny granules of birefringent minerals and iron ores in the cleared felspar indicate a high grade thermal metamorphism, and the writer now makes the suggestion that these may prove useful, as they have at Hartley, in revealing evidence of an earlier recrystallization and so showing the rock to be a hybrid.

The origin of peculiar ellipsoidal bodies within the recrystallized rocks has been discussed and chemical evidence adduced in support of the suggestion that they represent recrystallized zoned hornblende crystals. At the same time the possibility of contamination followed by recrystallization has not been entirely dismissed.

It has also been shown that another rock of mixed origin has arisen as a result of the contamination of the gabbro magma by calc-silicate sediments.

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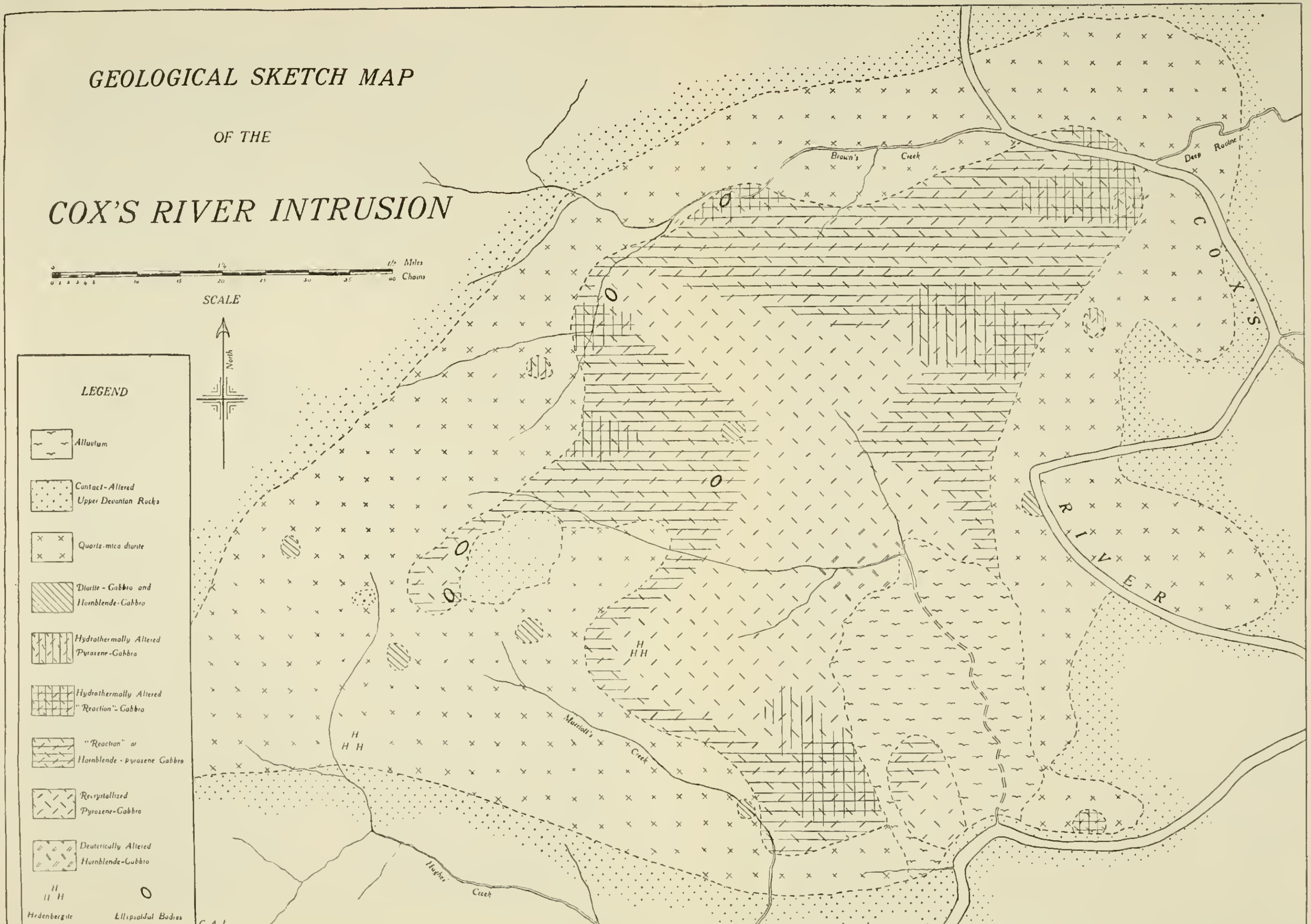
GEOLOGICAL SKETCH MAP
OF THE
COX'S RIVER INTRUSION
Miles
Chains
SCALE
North
LEGEND
Alluvium
Contact-Altered Upper Devonian Rocks
Quartz-mica diorite
Diorite-Gabbro and Hornblende-Gabbro
Hydrothermally Altered Pyroxene-Gabbro
Hydrothermally Altered "Reaction"-Gabbro
"Reaction" or Hornblende-pyroxene Gabbro
Recrystallized Pyroxene-Gabbro
Deuterically Altered Hornblende-Gabbro
Hedenbergite
Ellipsoidal Bodies
Brown's Creek
Deep Ravine
COX'S RIVER
Marriott's Creek
Hughes' Creek
C.A.I.